

TOROID II

Final Report 2007-2009

AFOSR University Nanosat Program



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1 Program Overview

The TORIOD II small satellite mission has been developed by faculty and students at Utah State University (USU) to measure vertical density profiles of the night time ionospheric plasma density distribution. Measurements will be achieved by using a tomographic reconstruction of extreme ultraviolet (EUV) night glow in the 1356Å emission band. The mission will focus on the Equatorial Anomaly regions, where the highest ionospheric plasma densities are observed and where equatorial plasma bubbles are observed to occur. In order to achieve the TORIOD II mission all spacecraft systems including satellite communication system, the navigation, Attitude determination and control, thermal must function within the Sun-Earth space environment. The science instrumentation for this mission will be accomplished using both a Sweeping Plasma Impedance Probe to measure local densities, as well as a EUV Photometer to measure night glow.

1.1 Mission

Figure 1 shows various disturbances found in the Equatorial Anomaly which the TORIOD II mission is targeted at. This data was collected from the TIMED/GUVI instrument. Note the dark regions found in the dense plasma regions. These dark regions are signatures of plasma bubbles that have risen up through the dense ionosphere. As an electromagnetic signal passes through the region around these bubbles, the signal can be scintillated, causing disruptions in communication. These bubbles are formed when the boundary separating the different plasma densities is perturbed, by some disturbance mechanism. Because of the Earth's magnetic field these disturbances are amplified and cause a bubble of lower density plasma to push into the higher density plasma above.

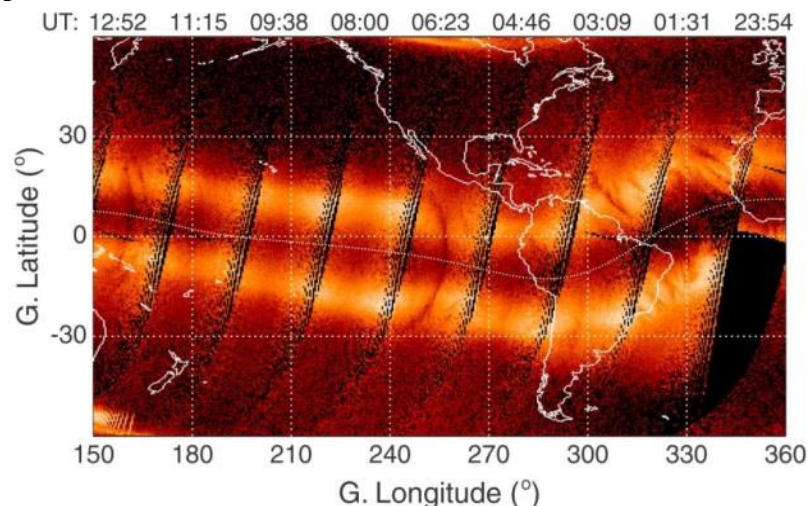


Figure 1 Equatorial Anomaly as Imaged by TIMED/GUVI at 1356Å

These bubbles range from being very small to very large. As can be seen in Figure 1, at about 260° longitude, there is a bubble which spans the entire equatorial anomaly. It should also be noted that these phenomena follow magnetic field lines. They also appear to be pushed by the neutral winds, creating “bubble arcs” across the Equatorial Anomaly.

These phenomena cause many effects on electromagnetic signals as they pass through. Scintillation of electromagnetic signals causes RF outages beneath the plasma bubbles. This causes loss of communications between space and ground assets, including loss of GPS. Government and commercial assets can be significantly impacted by the loss of space to ground communications. Diffraction is of interest for space-based geolocation of ground transmitters. Scintillation and diffraction can be better understood once a vertical profile of the ionosphere can be generated. There is a need for instrumentation which can measure the vertical plasma density across the entire low latitude regions.

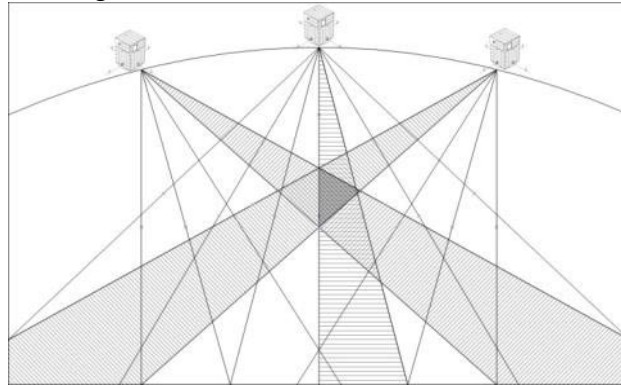


Figure 2 Tomographic Measurements of 1356Å EUV emissions

TOROID II will produce vertical plasma density profiles using tomographic reconstruction of optical measurements. Atomic oxygen recombination with electrons produces photons at 1356Å. Regions of high density plasma glow with this extreme ultraviolet light. There are no other emissions nearby in the spectrum during night observations. Observations of 1356Å light make it possible to measure the plasma density remotely. Many intersecting observations taken in the orbital plane make possible tomographic reconstruction of the vertical distribution of plasma density in the orbital plane. Figure 2 illustrates how these measurements will be taken and the tomographic reconstruction.

1.2 Organization

The TOROID II program was implemented using a team of students with a student program manager. The student team reported to the faculty advisor, Charles Swenson, who was assisted by an engineer from SDL, Chad Fish. A student program manager oversaw subsystem leads who worked with a small team of students. An organizational chart of the program is presented in Figure 3. The team was composed of students from Electrical and Computer Engineering and the Mechanical and Aerospace Engineering Departments at Utah State University. Over the course of the program some 25 students actively participated I in the design, fabrication, and testing of TOROID II. Approximately 8 other students participated peripherally through their senior projects. A list of the students who significantly participated is presented in **Error! Reference source not found.**

Table 1 TOROID II Student Organization

Sub-system	Name	Status	Major	Year
00 Program Manager	Daniel Perkins	Active	ECE	Graduate Student
00 Program Manager	Karl Burke	Inactive	ECE	Graduate Student
00 Systems	Nicholas Maughan	Active	MAE	Senior
00 Systems	Jana Coakley	Inactive	ECE	Senior
10 Structure	Steve Grover	Active	MAE	Senior
10 Structure	Keith Bradford	Active	MAE	Senior
10 Structure	Jonathon Howell	Inactive	MAE	Junior
20 Avionics	Cory Brinck	Active	ECE	Graduate Student
20 Avionics	Ryan Keith	Inactive	ECE	Senior
20 Avionics	Paul Rodriguez	Inactive	ECE	Senior
25 Software	Mark Andersen	Active	ECE	Senior
25 Software	Russell Grover	Inactive	ECE	Graduate Student
25 Software	Jared Crace	Inactive	ECE	Graduate Student
30 Communications	Daniel Perkins	Active	ECE	Graduate Student
30 Communications	Joshua Daley	Inactive	ECE	Senior
35 Ground Station	Joshua Daley	Inactive	ECE	Senior
35 Ground Station	Karl Burke	Inactive	ECE	Graduate Student
40 Power	Daniel Perkins	Active	ECE	Graduate Student
40 Power	Eric Stromberg	Active	MAE	Freshman
40 Power	Joshua Daley	Inactive	ECE	Senior
50 ADCS	Nicholas Maughan	Active	MAE	Senior
50 ADCS	Joshua Soelberg	Inactive	MAE	Senior
50 ADCS	Scott Jensen	Inactive	MAE	Graduate Student
70_Harness	Kristen Mortensen	Active	MAE	Senior
80_Thermal	Kristen Mortensen	Active	MAE	Senior
90_Science	Steve Burr	Active	ECE	Senior

ECE-Electrical and Computer Engineering

MAE-Mechanical and Aerospace Engineering

Inactive-Signifies that the person transferred schools or graduated before the end of the two years

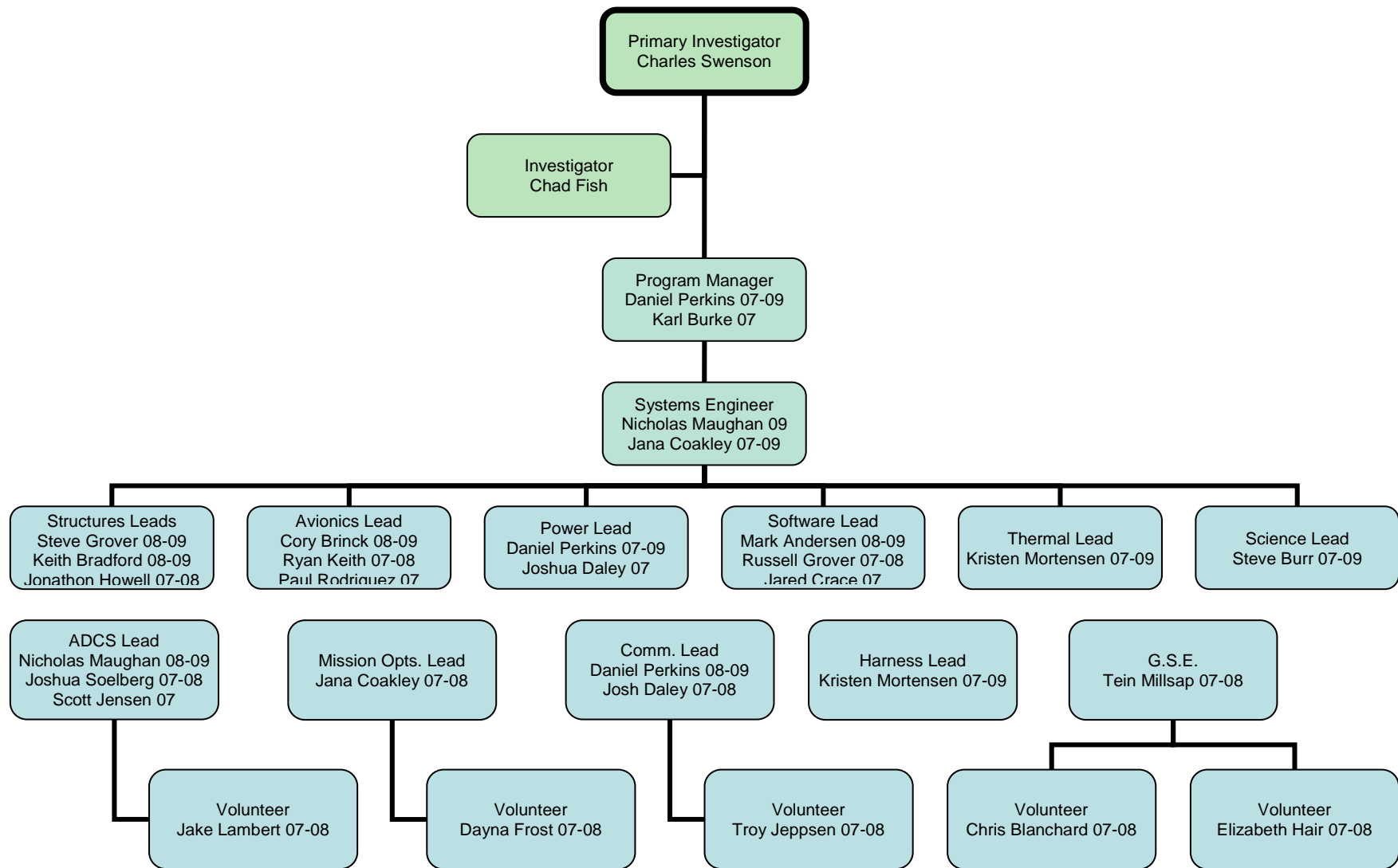


Figure 3 TORIOD II Organizational Structure

2 Systems Overview

TOROID II is a small microsatellite developed by students at USU. It uses the USUSat II bus, which is a second generation design, retaining heritage electronics and software from its predecessors at USU. An exploded view of the spacecraft components is presented in Figure 4. The USUSat II bus is capability driven, modular design. This allows additional payloads and experiments as they become available. The spacecraft bus provides basic resources such as power, data handling, communications, as well as structural and thermal interfaces in support of a wide range of payloads and experiments, such as the photometer scientific instrument which is part of this mission. The TOROID II design and team was divided into several subsystems along traditional spacecraft systems engineering patterns. Each subsystem was able to develop requirements based upon the mission and the system level requirements. TOROID II is organized as follows:

- Structure
- Command and Data Handling
- Software
- Communications
- Ground Station
- Power
- Attitude Determination and Control
- Mechanisms
- Harness
- Thermal
- Science

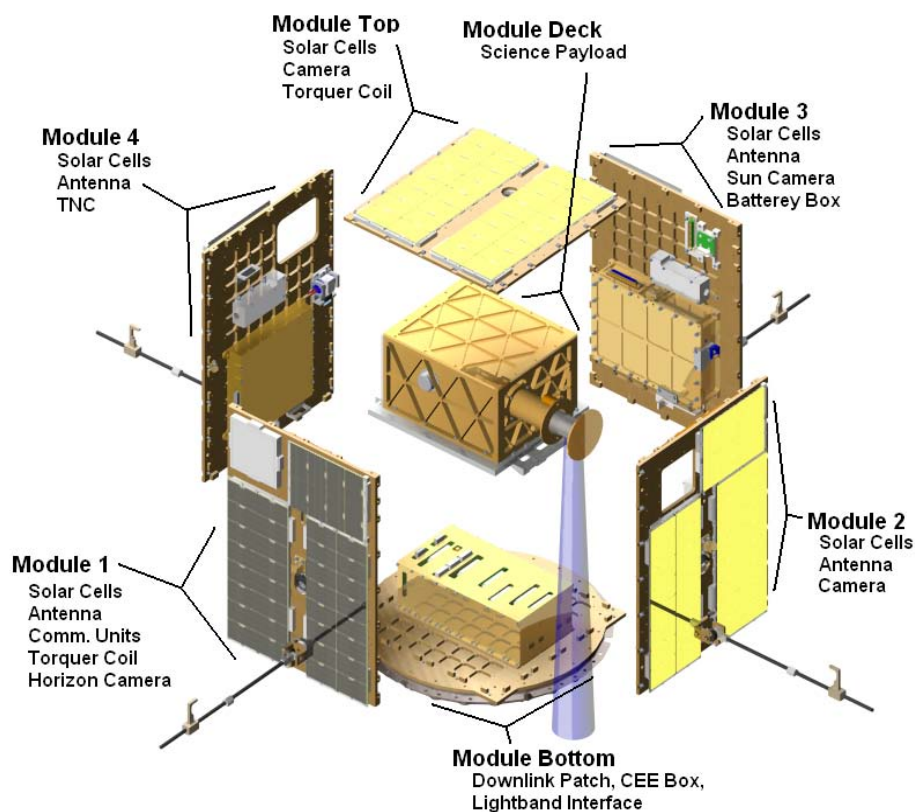


Figure 4 An exploded view of the TOROID II spacecraft components

The following sections will outline each subsystem and describe the progress made in those areas over the past two years.

2.1 Structure

The structure used on TOROID II has been designed in a small geometric package in order to be accommodated by both NASA and Air Force launch systems. The geometry of the primary structure is 13 inches square and 19 inches tall. By using a rectangular box, the number of structural parts is minimized, and provides a highly efficient use of space on the interior.

TOROID II's structure has also been designed with modularity in mind. This allows each module to be sub-assembled and tested independently. The modules are represented by each of the six panels of the spacecraft. To further the modularity of the spacecraft, each panel employs a standardized bolt pattern in an orthogrid. This allows internal components to be arranged easily and allow for balance of the spacecraft.

The structure is an evolution of the USUSat I structure, which was also developed at USU. The structure is designed as a rectangular cube, which directly interfaces to NASA and Air Force launch systems via the Lightband separation system. The structure is manufactured of 6061-T6 Aluminum, and is manufactured into a closed orthogrid pattern. The orthogrid panels have a rib thickness of 0.25" and a web thickness of 0.03".

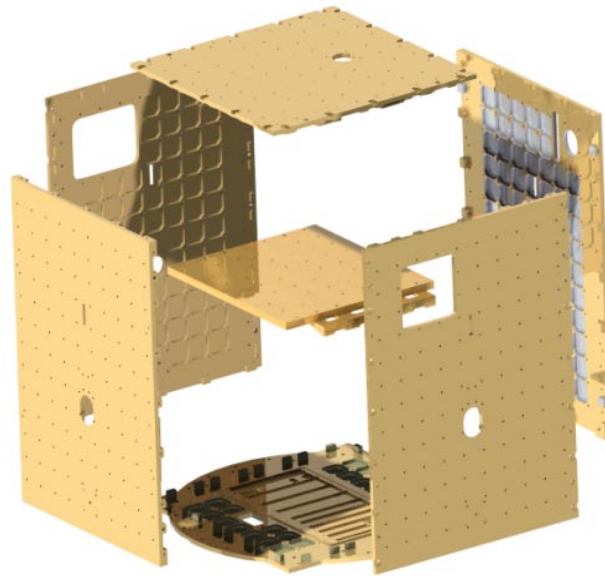


Figure 5 Orthogrid Structure

This orthogrid pattern is centered in each panel, leaving an edge around each module a homogenous thickness to reinforce the load paths around the joints. The torque coils used in Attitude Control are directly milled out of the same structure on three panels, as shown in Figure 4. The coils are then directly wrapped around the structure. Additionally, the Central Electronics Enclosure is also integrated onto the structure, increasing stiffness and thermal conduction. Four monopole antennas will be attached to the base of the four rectangular modules. This eliminates the need for a deployable in our former communications system design.

Since 2007, the structures subsystem has made changes to the design, which has lead to greater stability and reduced the risk of the overall system. The science deck plate, which can be seen in the middle of Figure 5, was designed to be made using a technique referred to as additive

manufacturing. This technique was deemed to be too risky because of a lack of heritage, so the deck was redesigned from solid materials, analyzed, and documented.

One of the major improvements for this system was the completion of the Finite Element Analysis (FEA). The FEA results showed that our satellite had a stiffness first mode of 162.5 Hz, which is well above the 100 Hz first mode minimum required by NASA. The structure was assembled and vibe tested. These tests showed a first mode of 202 Hz.

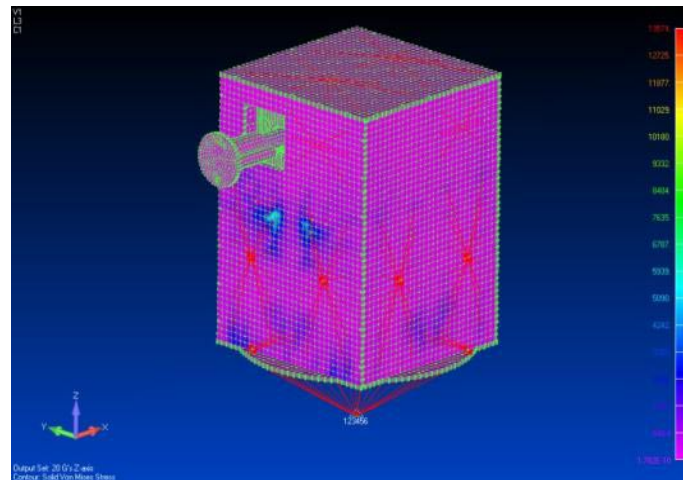


Figure 6 FEA Analysis

The torque coils are integrated to the structure and the wrapping of these coils was completed. The coils were tested and documented and all three coils are in operating order. The Structural design and analysis of components such as the motor, bearings, and deployment mechanism of the TOROID photometer has been completed. A prototype of the photometer has been manufactured and will soon be assembled and ready for science and structural testing. The final design of the structure and assembly process has been documented.

2.2 Command and Data Handling

Integrated into a single bus system, the Command and Data Handling (C&DH) system includes:

- The central computer
- Telemetry electronics
- The attitude determination and control system
- portions of the science system
- power management electronics

Exceptions to this integration are the communications electronics and portions of the science electronics. This system is complete and currently completing functional testing.

Previously the C&DH system employed a low power design, such as those used in commercial PDA's. USU has developed and tested a complete Command and Control system centered on these low power processors. This system, based on this technology, is capable of 80 MIPS while consuming less than two watts of power. In addition to being a low power system, the Command and Data system handling has taken steps to mitigate radiation effects. The system is designed to handle both Single Event Latchups (SEL) and Single Event Upsets (SEU).

In order to mitigate against the effect of SEL's, each electronics board in the system employs current sensors monitored by the CPU. When a current passes a given value, the CPU will power cycle the board in question, releasing the latchup. The Power Management system monitors the CPU itself, and will cycle the entire system should a SEL be detected in the CPU. SEU's are mitigated through the use of Triple Modular Redundant (TMR) memory.



Figure 7 C&DH System in Clean Room

Since 2007 the C&DH system has undergone extensive debugging. Through testing it was found that the I/O board SPI interface has not been working. This problem was investigated and it was found that the I/O board produced the correct control, data, and address signals but that the slave devices (Motor Board, Power Board 2), were not responding to the signals. The Power Board 2 (PB2) FPGA was written to output data in a 27 bit block, as would be seen in a Simulink simulation, while the I/O board can only read in 8 bits at a time. Even so, in practice the PB2 FPGA did not respond at all to the I/O board signals when tested with the logic analyzer.

The Motor Board is another slave device on the SPI bus. It also does not respond to the I/O board. The Motor Board is missing one of two FPGAs. It was originally thought that it did not need this FPGA because we were no longer planning on using reaction wheels and gimbals, for which it was originally designed. One reason that the motor board is not responding could be that it needs the connection provided by the other FPGA to the SPI MISO (Master In Slave Out) line. This signal is connected to the slave devices in a wired-AND configuration, meaning that any of the slave MISO signals goes low, they all go low.

This is not the same problem with the PB2 SPI communication, because PB2 was tested without the Motor Board connected, so the Motor Board MISO buffer could not be driving the bus low. PB2 also always output a logic high on the MISO line, as it should if it is not outputting data.

It was decided to completely replace the Motor Board, as it was not designed to control torque coils. It was thought that the Motor Board could be used to control torque coils with its stepper motor drivers, however after reading about the stepper motor driver outputs on the data sheets, it was found that these would not do.

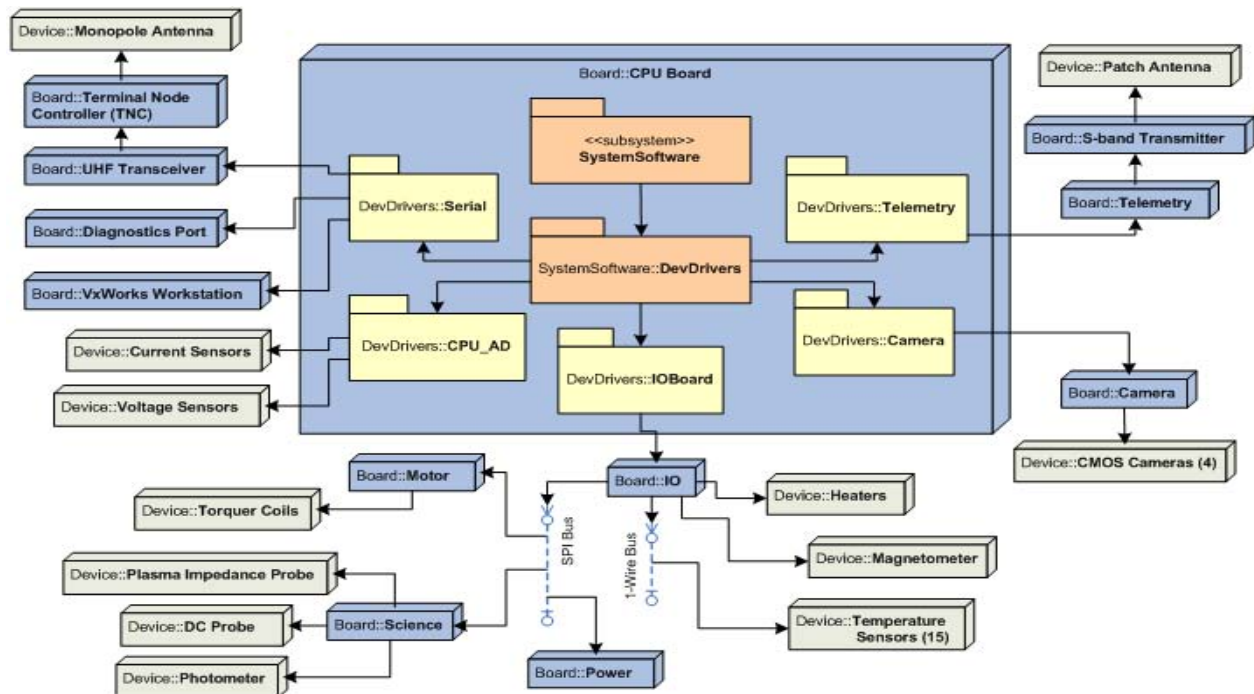
A simple torque coil controller circuit was implemented to replace the Motor Board. It uses National Semiconductor H-bridges to control current through the coils. A driver was written to manage the digital signals needed. Originally the plan was to use the I/O Board digital I/O, but we could not get a response from the I/O board, so the CPU Board I/O (Port D) was used. The circuits were implemented on the old structure and tested, there was a short in one of the torque coils which caused problems and damaged 2 of the circuits during testing, however, one works properly and the appropriate electric field is produced when activated. Future work should involve building new circuits for the new structure and debugging the I/O board digital I/O, as the CPU Port D will not provide the six signals needed to interface to the H-bridges.

The camera board had not been obtaining usable pictures. In order to determine the problem a PCI card supplied by the camera chip manufacturer was installed on an old Windows 98 PC, which was able to read images off of the cameras. The problem was then found to be due to faulty cables, uncalibrated optics, and noise from the board itself. The optics were changed, but will need appropriate means of stabilizing the lenses before they would be reliable for flight. We have 2 working cables and 4 cameras, so 2 more cables are needed. We have the cable but need the connectors. A noise subtraction program was written in Matlab which cleaned up the noisy images and could easily be written in C to be used on the satellite.

The I/O board analog I/O was not correctly reading in values. These are used to monitor voltages and to read the magnetometer. The problem was found to be a missing ferrite bead which connects the 12V power supply to the op-amps which are used to appropriately scale the voltage before it is sampled by the A/D converters. The board was sent over to the Space Dynamics Lab's SMT Lab to be fixed, and the analog I/O now works properly.

2.3 Software

The TOROID II software subsystem coordinates all of the subsystems providing a fully functional system. Figure 7 shows the interface between the software system, the hardware, and the layers of the software. The most fundamental layer is the device drivers, which interface to the VxWorks, real time operating system. Above the Operating system is the Control system, Data Collection, and analysis and communication. All of these systems are controlled via system management software. Communication with the satellite has been designed so the satellite appears as a computer to the operator, allowing an easy interface to the ground. Additionally, a GUI has been developed using LabVIEW to allow users to interact and control the spacecraft.



As part of the TOROID II mission, a ground station has been developed at the Space Dynamics Lab. The ground station is able to communicate with TOROID II using both the UHF command link, as well as the S-band downlink. The hardware consists of a 4.5 m parabolic antenna used for the downlink, and a yagi array for the command link. The command link frequency is in an amateur band; thus, several members of the TOROID II team are licensed amateur operators and have coordinated with the amateur radio community.

The Ground Station software has been adapted from the MercuryGS software package from Stanford University, so it will display the Ground Station data in real time. Tracking is accomplished using Predict, which has been interfaced to the antenna controllers.



Figure 9 Operating Ground Station

The Ground Station currently is operational in the UHF band. The USUsat team, along with other teams that plan on using the station, have been in contact with amateur satellites that are currently in orbit.

2.6 Power

The TOROID II Power system includes the power management electronics, batteries and solar cells. The batteries used in the system have been supplied by the Air Force Research Laboratory. The solar cells are triple junction GaAS cells, providing efficiency between 21% and 24 %.

The power management electronics consists of four electronics boards. These boards provide watchdog timers for SEL mitigation, as well as power conditioning. Power conditioning is accomplished via DC/DC converters. This provides the satellite with ± 3.3 , ± 5 , ± 12 , and 24 V systems, as well as the 15V unregulated bus. The power management electronics also provides the satellite with power inhibits, as required by launch vehicle standards.

The power components of TOROID were well established by 2007. The highlights since 2007 include the manufacturing of the solar panels and the discovery that the power inhibit system has critical flaws that do not allow it to work properly.

The Solar Cells for TOROID have progressed immensely over the last six months. The assembly process was based on Tyler Goudie's assembly procedure written several years ago. Working closely with Engineers from USU's Space Dynamics Laboratory (SDL), the procedure

was modified and corrected based on SDL's own written procedure and the ideas from Tyler's procedure. The modifications required some manufacturing of templates, standoff holders, and assembly components that took place at the USU machine shop. The cells were individually tested to find the I-V curves that would later be used to make the best matches possible and allow for the best functionality. The modified procedure is different from the TOROID I design in that the cells were assembled in a slightly different manner. Instead of baking the cells, pure vacuum pressure was used which gave different and overall better results in the assembly of the cell strings. SDL helped immensely in providing accommodations for the process with a vacuum chamber, thermal cycle machine, and an approved clean room. Further testing of these new solar panels will help us get a better estimate of our overall power production and help us streamline our power budget.

While performing testing on the whole power system, it was discovered that the inhibit circuitry turned its self off before it could properly close the connection between the batteries/solar panels and the operating components of the satellite. Efforts were made in the attempt to come up with new circuitry. As to date, there is still no working circuitry for this important component.

2.7 Attitude Determination and Control

The TOROID II ADCS strategy centers on a momentum bias system, supplemented by three axis magnetic control. This provides the system with a highly accurate, yet simple design. This also includes an experiment using a three axis magnetic control system. This system will provide ± 1 degree accuracy, as needed by the science instrument.

To increase the accuracy of the measurements Attitude Determination is accomplished via a three axis fluxgate magnetometer, CMOS sun and star sensors, and a Kalman filter.

The work and tasks that have been accomplished on the TOROID Attitude Determination and Control System (ADCS) since 2007 have been primarily focused on preparing the hardware and software for flight status. The attitude control and determination hardware and software have been in development for several years. Modifications and additions were made to the existing supervisor, controller and determination software. Part of this modification included defining the message structure of the software so that remote analysis of the ADCS could be performed. The definition of the ADCS operating modes and an operational timeline were developed, this helped establish an overall operational timeline for TOROID. Testing and calibration was performed on the three-axis magnetometer which is primary attitude determination sensor. This testing showed that a detailed analysis of the components onboard the satellite must be performed so that magnetic interference bias can be modeled and accounted for in the overall attitude determination. Testing and initial calibration was also performed on the CMOS cameras which are secondary sensors. The results of the testing on the CMOS cameras revealed some focal length modifications were needed. The satellite structure was redesigned to be fabricated using space qualified materials, the torque coils were assembled on the new panels and tested to ensure the required magnetic field was being produced. Previously the torque coils were to be controlled with stepper motor controllers, the board was redesigned to use an H-bridge circuit. An integral part of the attitude control solution was the inclusion of a momentum bias, analysis to determine

the amount of momentum bias was computed. It was concluded that the science instrument would be able to provide the needed momentum bias and an additional wheel would not be needed. Attitude knowledge requirements were also revised. In order for the science mission to produce tomographic reconstruction attitude knowledge of less than 1° would be needed. This attitude knowledge would not be available on orbit with the then current attitude hardware. A trade study of various hardware/software solutions was conducted and resulted in the selection of using post analysis of star field imagery to provide the required attitude knowledge.

2.8 Mechanisms

In the past there were two mechanisms on TOROID I, not including the mechanism used in the instrument, these include the antenna hinge and the antenna release mechanism. These mechanisms were removed from the project after the size of the launch envelope increased, which allowed us to design fixed antennas.

The mechanism for the science instrument has been redesigned and manufactured. In the past designs, the whole payload box shifted places inside the satellite when it was deployed. This was due to the limitations on the envelope size. With the envelope increase we were able to put the mechanism on the outside and reduce the risk of damaging the science components layout when it deployed. The mechanism consists of a sliding cover that prevents contaminants from entering into the payload cavity. After launch and separation, two frangibolt actuators will release the mechanism, and with the use of constant force springs the cover will slide away from the payload opening allowing light to enter the sensitive science instrument.

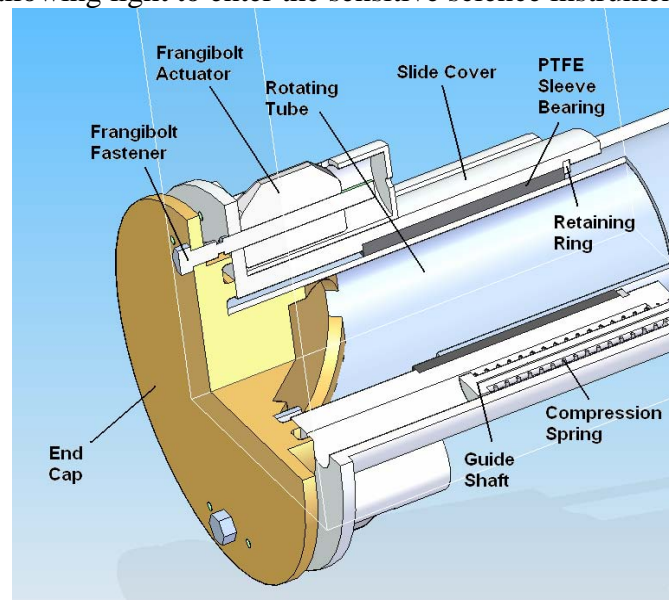


Figure 10 Sliding mechanism

2.9 Thermal

The thermal control system on TOROID II uses both passive and active thermal elements to control the temperature of the spacecraft. A series of thermal sensors and heaters are located near

critical components to maintain the proper thermal environment. A detailed thermal analysis has been performed using SINDA. As the satellite is covered in solar cells, the use of MLI blanketing is unnecessary. The thermal design of TOROID II shows it capable of surviving in a variety of orbits, including LEO (185 km – 1000 km) and GTO. Figure 10 shows the temperature predictions for TOROID II. This same model will be used to correlate on orbit temperatures obtained via telemetry.

Figure 11 Hot and Cold thermal cycles

2.10 Science

The primary instrument for the TOROID II mission is an Extreme Ultraviolet (EUV) Photometer. The EUV Photometer will detect EUV intensities for tomographic reconstruction of the full vertical plasma density profile of the ionosphere. A conceptual design of the instrument is shown in Figure 11. The instrument directs light to a microchannel sensor with a rotating mirror. These photon counts are downlinked for tomographic reconstruction. The mirror also acts as a narrow bandpass filter.

In addition to the EUV Photometer, a plasma impedance probe that will provide high fidelity readings of plasma density at the orbit altitude, giving local data, temperature, collision rate, and cyclotron frequency. The probe is one of the command link antennas that have been duplexed using the splitter board.

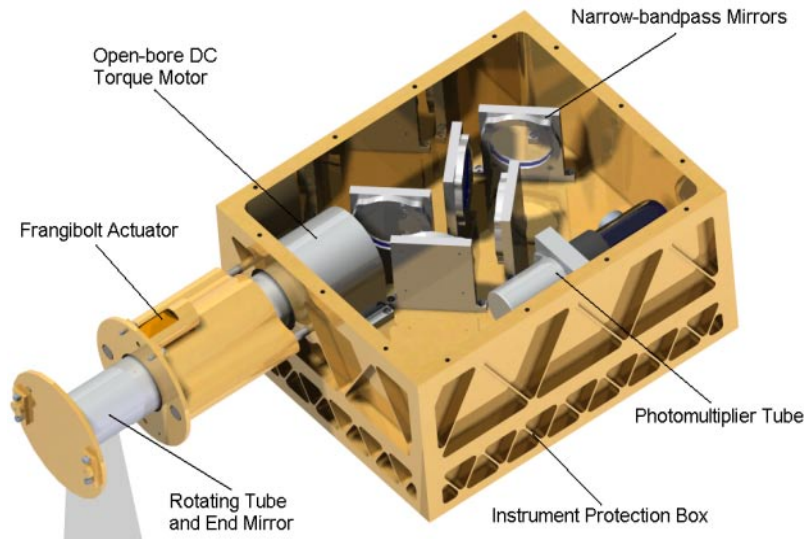


Figure 12 Science Payload

3 Conclusions and Lessons Learned

Over the period of this grant, the TOROID II program has finalized the design and completed a majority of the subsystem fabrication and has been engaging in functional testing. The team presented a Preliminary Design Review in August 2007 at the USU/AIAA Small Satellite Conference, and finished the Critical Design review on March 19th, 2008. The TOROID II team participated in the final competition review January 19-21 in Albuquerque, NM. Over the course of this program detailed sets of mission, system and subsystem requirements have been developed. The fabrication of the spacecraft is 95% complete, and is awaiting the completion of parts of the ADCS system and the science instrument. Over 33 students were involved with 25 of them being extensively trained in spacecraft systems engineering. Table 2 give an overview status of the TOROID II program.

The results of the final competition review for the University Nanosatellite Program with the TOROID II spacecraft not finishing in the top three positions was a significant event for all involved at Utah State University, but not surprizing. At the start of the competition USU had significant advantages with existing USUSat III hardware in hand but almost no experienced students to begin with. The team had support from both the Space Dynamics Laboratory but very limited support from USU faculty members given that Dr Swenson was on sabbatical at NASA HQ during this program. TOROID has clearly been an outstanding success for students involved with the program. The anecdotal metric used for judging success is if they can find a “great job” after school making use of their USUSat experience. The evidence of this is both abundant and outstanding. Students in the USUSat program were directly targeted and sought after by both government and the aerospace industry and most graduating members received multiple job offers. Even students who were mediocre scholastically were sought after and rapidly hired because of the particular experiences the USUSat program gave them. It was very clear to all students involved that the USUSat experience created opportunities for them that would not have been possible otherwise.

The USUSat program has been built up around the concept of volunteerism and as a topic area for senior design projects or thesis research. About four or five student positions are directly supported by the USUSat program. One or two additional positions are typically made available on externally funded research that is synergistic with USUSat. The USUSat program is not directly a part of the curriculum in either the ECE or MAE Departments. The only way students can receive academic credit for participating is through a senior design or a graduate research project that is individual to them. The USUSat team, supported in this way, has generally been small and vulnerable to the loss of key students to other research enterprises at USU or job opportunities. On this basis the USU team does not appear to be as well motivated as those at the schools which ranked highly in the competition. These schools approach the student design program differently. Such programs are fully integrated as part of the curriculum for which they get academic credit. Students must choose from a number of projects including the student satellite program to complete their undergraduate or Master of Engineering design project requirements. They are graded on their participation and contribution to the effort and the project funding is used for hardware only. All three schools which placed highly in the University Nanosatellite Competition had student teams motivated in this way. It appears unlikely that USU's volunteerism approach to the student team will be able to successfully compete in the future. This is in large part due to waning motivation of the faculty and professional advisors that are critical to the program. Utah State University did not propose for the latest round of the Air Force University Nanosatellite Program but would like to participate in some future rounds of the opportunity.

Table 2: TOROID II Status

System	Design Completion	Hardware		
		Parts on Hand	USU Manufactured	External Source or Purchased
Structure	100%	100%	50%	50 %
Deployables	90%	90%	60 %	40 %
Internal structure	100%	90 %	90 %	10%
Lightband				100%
Solar Cells		100%	80%	100%
Battery	100%	100 %	50%	50%
Power Regulation	100%	100%		
Transmitter	100%			100%
Receiver	100%	100%	50 %	50%
Comm. Electronics	100%	100%	10%	40%
Antennas and TNC	85%	75%	50%	
Ground Station	95%	95%	10%	
Science Instrument	75%	100%		
C&DH electronics	100%	100%		
Cameras	100%	100%	50 %	50 %
Magnetometer	100%	100%		
Software	90%	80%	20%	
Wiring harness	100%	100 %		20%